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13. ABSTRACT (Maximum 200 words) This report is a summary of the work performed under Contract DAAH04-96-C-0027. The primary efforts were : (1) organization and technical participation in a workshop on cyclostationary processes in the summer of 1996; (2) a Wold decomposition for cyclostationary sequences, (3) periodically correlated processes in two dimensions; (4) development of algorithms for detecting harmonic coherence; (5) demonstration of presence of cyclostationary signals in battlefield acoustics; (6) development of necessary and sufficient conditions for the solutions of a first order autoregression with almost periodic coefficients to remain bounded; (7) aspects of spectral theory for completely regular periodically correlated processes; (8) scientific interchange with visitors from the former soviet union.				
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**Theory and Inference for Cyclostationary
Random and Non-Random Functions**

Final Report on Contract DAAH04-96-C-0027

March 17, 2000

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1 Introduction

The purpose of this report is to document the work conducted on contract DAAH04-96-C-0027 in the period 15 May 1996 through 31 October 1999.

The efforts on this contract were directed toward further development of the theory of periodically correlated (cyclostationary) and almost periodically correlated processes and to the exploitation of their structure in applications to battlefield acoustics. In addition to showing the presence of cyclostationary signals in battlefield acoustical data, the ideas of spectral coherence helped suggest methods for exploiting the presence of *harmonic coherence* in battlefield acoustical data. This elaboration, and the development and demonstration of related ideas, has taken much of our attention.

2 Summary of Results

The major areas of work are summarized in the following paragraphs.

The Workshop on Cyclostationary Processes was held at Universite de Marne-la-Valee near Paris, France, for the days July 1 - July 3, 1996. The workshop was small, permitting discussions at a depth and a wide range of talks, including expository, theoretical and practical talks, to be appreciated in one meeting. The proceedings [4] were published as Center for Stochastic Processes (Dept. of Statistics, Chapel Hill) Technical Report No. 485 and was submitted to ARO as a Technical Report. The contents of the proceedings are:

1. H. Hurd and T. Koski, "On the Wold Isomorphism and Wold Decomposition for Prediction of Cyclostationary Sequences".
2. P. Rostaing, T. Pitarque and E. Thierry, "A Theoretical Study of the Single Cycle Detector with Application to Sonar Signals".
3. P. Loubaton, "On the use of cyclostationarity in the context of blind equalization".
4. H. Hurd "Spectral Coherence Measurements of Accelerometer Signals Taken from a Faulty Gear System".
5. D. Dehay, "Frequency Determination for some Almost periodically Correlated Sequences".

6. L. Izzo and A. Napolitano, "Characterization of Higher-Order Almost Periodically Correlated Time Series".
7. D. Dehay and H. Hurd, "Spectral estimation for a strongly periodically correlated random field defined on Z^2 ".
8. D. Alpay, A. Chevreuil and P. Loubaton, "An extension problem for discrete time periodically correlated stochastic processes".

The Wold Isomorphism for Cyclostationary Sequences Work on this topic with Professor Timo Koski of Sweden began before the inception of this contract. A preliminary version of the work appears in the Proceedings of the workshop and was refined to produce a more concise result which was published as Center for Stochastic Processes (Dept. of Statistics, Chapel Hill) Technical Report No. 484 [3]. The main thrust of this work was to make precise a notion of isomorphism between a cyclostationary stochastic sequences and cyclostationary deterministic sequences. This notion has been used often in engineering publications and its clarification was considered a worthy task.

Periodically Correlated processes in two dimensions On the connection between unitary operators and PC fields was begun in the 1994 conference paper by Hurd and Kallianpur [1]. An elaboration of these preliminary results was documented in report no. 448 [5] for the Center for Stochastic Processes.

The issue of spectral density estimation for two-dimensional PC fields was treated in a conference paper [2] for the workshop on cyclostationary processes discussed above.

Harmonic Coherence Our previous uses of *spectral coherence* as a means to detect the presence of cyclostationary structure naturally lead to consideration of *harmonic coherence* for signals having harmonic structure. Since signals of this sort would be expected in acoustic signals from heavy ground vehicles, such as tanks and trucks, we began to investigate the application of harmonic coherence to battlefield acoustics. Our first effort in this direction [6] showed the plausible existence of harmonic coherence in these signals, and demonstrated methods for detecting the presence of harmonic coherence.

The next effort [7] resulted in methods for expressing the statistical significance of the harmonic coherence found in battlefield acoustical signals

and showed how this coherence could be a basis for (a) de-cluttering gram displays and (b) improvement of localization and tracking.

Our most recent effort in this direction resulted in the demonstration of effects of interfering spectral lines on harmonic coherence [8].

Cyclostationary Signals in the Battlefield This effort demonstrated the presence of signals having harmonic structure but also cyclostationary structure [9]. It was shown that cyclostationary signal processing methods may provide features that will aid in target classification and association.

Parametric Models for Almost Periodically Correlated Processes The first work was concerned with the first order autoregressive model with almost periodic coefficients. We obtained necessary and sufficient conditions on the coefficients for the solutions to remain bounded. This manuscript [10] has been submitted for publication.

Spectral Theory for Periodically Correlated Processes This work was concerned with completely regular (meaning of full rank) periodically correlated sequences and their prediction. The manuscript is being issued as a report for the Center for Stochastic Processes, Department of Statistics, University of North Carolina at Chapel Hill.

Visitors This contract supported a number of visitors, some of which are from the former Soviet Union, who have been involved in research on periodically correlated (cyclostationary) processes.

Dr. M.I. Fortus and Dr. V.G. Alekseev, both of the Institute for Atmospheric Physics, Academy of Science of Russia, visited for 1 month in 1997 under support of this contract. New collaborative work was begun on the use of cyclostationary structure in meteorological and other geo-physical time series. Dr. Akiva Yaglom also participated for 1 week during this time period.

Dr. Andrzej Makagon, Hampton University, visited for 2 weeks. During this time the structural problems of AR(1) models with periodic and almost periodic coefficients were examined. This lead to the manuscript with A. Makagon and A.G. Miamee, entitled "On AR(1) models with periodic and almost periodic coefficients",

Issues of spectral analysis for completely regular PC sequences were studied, leading to the manuscript with A. Makagon, "Spectral analysis of completely regular periodically correlated sequences",

Dr. Jacek Leskow, University of California at Santa Barbara, visited for 2 weeks. The problem of time series analysis for almost PC processes produced by autoregressions with almost periodic coefficients was addressed.

Professors B. Yavorskiy and Y. Dragan, from the Ukraine, who together have written several books containing material on PC processes, visited for one month in early 1998. Their view of the correlation and spectral theory for PC processes is based on randomness and infinite time averages, (in a Besicovitch almost periodic function sense). A manuscript describing this view and introducing a new sense of harmonizability has been produced.

Dr. A.G. Miamee, Hampton University, visited for 4 weeks. During this time the issues of spectral multiplicity for PC processes and prediction for PC sequence of less than full rank were examined.

Book manuscript: "Periodically Correlated Random Sequences, Spectral Theory and Practice" Effort has been devoted to this book manuscript. It will treat the basic correlation and spectral theory, the Wold decomposition and prediction for multivariate periodically correlated sequences.

References

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